Tropospheric Infrared Mapping Spectrometers (TIMS) for CO Measurements With Much Improved Vertical, Temporal and Spatial Resolution, Especially in the Lower Troposphere by Utilizing Both the 2.3 and 4.7 μm Regions

John (Jack) B Kumer, A.E. Roche, R.L. Rairden, J.L. Mergenthaler

Lockheed Martin Advanced tech. Center, LMATC ADCS 255 2, 3251 Hanover St., Palo Alto, 94306

and R.B. Chatfield

NASA Ames Research Center

Abstract- The recently released report of the National Research Council " Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" describes requirements for improved atmospheric measurements to gain crucial understanding for air quality, climate change, and weather. Improved vertical and horizontal resolution, temporal resolution and coverage are required. Our project is focused on demonstrating a technology; Tropospheric Infrared Mapping Spectrometers (TIMS) that would provide considerably improve measurements of CO, commensurate with the NRC report requirements. Nadir radiance acquired at high spectral resolution, the order a few tenths cm^{-1}, in the regions of the CO bands near 2.3 μm (solar reflective, SR) and 4.7 μm (thermal emissive, TIR), together with the low noise design (signal photon statistics dominated) would provide for CO retrieval with improved vertical information, in three independent layers including the lowest several km layer. For LEO deployment the data are acquired on contiguous footprints the order 2 km (SR)and 4 km (TIR) at nadir, and swath widths the order 2800 km providing daily global coverage in the SR and twice daily in the TIR. In GEO deployment coverage area is traded for increased temporal resolution, e.g., several 1000 km on a side, repeatedly per hour. The primary measurement goal is CO, but the spectra contain information that facilitates retrieval of column CH_4, and H_2O partial columns including considerable improvement in the boundary layer. The technology uses low noise 2D arrays fed by a grating spectrometer. There are no moving parts. The design is compact. This facilitates, if desired, added spectral regions for measurements of additional species, e.g., tropospheric ozone partial columns in the 9.6 um band and/or CO_2 column in a band near 2.1 μm. We will present the TIMS instrument and measurement concept, its heritage, our demonstration approach, and preliminary test results.

I. INTRODUCTION

Overall, the TIMS effort addresses the NASA Strategic goal 3A: "*Study planet earth from space to advance scientific understanding and meet societal needs*", and more specifically to NASA Research Objective 3A.1: "*Understand and improve predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition*."

These high priority needs for better understanding of the connection between atmospheric composition and air quality as has been called out in NASA Research Objective 3A.1 have been delineated recently in various reports. A most important example being the Decadal Survey report by the National Research Council (NRC) [1].

In recommending a Global Atmospheric Composition Mission (GACM), and a Geostationary Coastal and Air Pollution Events Mission (GEO-CAPE), the report notes that --- *'Current observation system for air quality are inadequate to monitor population exposure and develop effective emission control strategies"*. The report calls for the measurement of O_3 and its precursors, and key trace gases including CO and HCHO, and places high priority on

- Sufficient vertical resolution to detect the presence, transport, and chemical transformation of atmospheric layers from surface to the stratosphere and
- high spatial and temporal resolution in order to track emissions of ozone and aerosol precursors; pollutant transport into, across, and out of North, Central, and South America; and to detect large puff releases from environmental disasters.

Specifically recommended atmospheric composition measurements and attributes addressing air quality include

- Broad areal coverage with improved spatial resolution, e.g., 5 to 10 km footprints at nadir
- Rapid temporal refresh, hourly from GEO for example
- Improved vertical resolution in the troposphere, e.g., as can be achieved in nadir view by
  - Simultaneous and highly spectrally resolved measurement of CO in the 2.33 and 4.68 μm bands

The IIP TIMS is currently in development to demonstrate the capability for this type of space borne measurement for tropospheric CO, with CH_4 and H_2O as secondary objectives. But as discussed below, the as discussed below, application of the TIMS approach in several additional spectral regions can also provide similar measurements for O_3, HCHO, N_2O, and CO_2.

Such measurements are in direct support of Earth Science Focus Area "Atmospheric Composition", addressing for example the key science questions -*What are the effects of global atmospheric chemical and climate changes on regional air quality; and –How will future changes in atmospheric composition affect ozone, climate, and global air quality.*

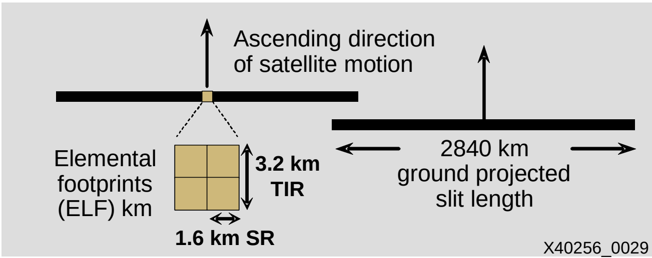

Fig. 1. Shows overlapping swaths of ascending nodes.

II. SPACE BORNE CONCEPT

We outline here a concept for the space borne application of the IIP-TIMS technology to illustrate its capability for the precision mapping of the global distribution and transport of tropospheric gases involved in air quality and global warming.

For a LEO mission, the instrument operates in a nadir-looking configuration with field of view coverage as illustrated in Fig. 1.

Anamorphic field widening front end optics provide a ± 57 deg or 2840 km projected cross-track swath perpendicular to the satellite motion, with ~ 1.6 km footprint at nadir along the swath in the Solar Reflective (SR) region of CO absorption near 2.33 µm, and 3.2 km in the Thermal InfraRed (SR) region of CO absorption near 4.68 µm. Data are acquired in a wide pushbroom swath of contiguous footprints with swaths wide enough to allow the ends to overlap for both ascending, and descending nodes for a sun synchronous polar orbiting case. This provides twice daily global coverage for the TIR CO band, and once daily for the SR CO band.

For the case of a geostationary orbit, coverage is achieved by a scan mirror that pushbrooms the slit across the disk. Sub satellite point diffraction limited footprints of 1.6 and 3.2 km in the SR and TIR, respectively, can be achieved with a 13.6 cm aperture, and the slit would project along a 1640 km swath width.

Table I summarizes the target species, measurement type, and associated spectral and radiometric parameters for the space borne mission. With these measurements the space deployed MAC TIMS retrieval expectations are:

- CO in the boundary layer (BL) and two layers above with respective precisions [2] the order 10, 5 and 3 %.
- H2O retrieval in the BL and more than 2 layers above
- CH4 column retrieval
- some tropospheric O_3 information

Table I Measurement goals for the space borne TIMS concept

Species to be measured primary, secondary	Measurement type[A]	spectral range ν_1 to ν_2 (cm^{-1})	Goal $\Delta\nu$ (cm^{-1})	goal NEdN[B]
CO, H_2O, O_3	TIR	2112 to 2160	0.20	1.0[X]
CO, H_2O, CH_4	SR	4281 to 4301	0.13	1.0

Notes: A- Either Solar Reflective (SR) or Thermal InfraRed (TIR); B- noise equivalent radiance difference in units nW/(cm^2 sr cm^{-1}); X-assuming albedo=0.1 for SR channels & @ 260K scene temperature for TIR channels

III. DESIGN GOALS AND APPROACH

TIMS comprises two separate high spectral resolution grating spectrometer modules, operating respectively in the CO TIR band near 4.68 µm, and the CO SR band near 2.33 µm. Table II lists the module optical parameters.

TABLE II
TIMS modules optical parameters

regions	Aperture	FOV Along Slit	FOV (pix)
TIR	3.9 cm	10.4 deg	0.18 mrad
SR	3.5 cm	10.4 deg	0.18 mrad

Both modules use the “solid state” spectrometer technique in which a fixed grating is coupled with a HgCdTe 1024x1024 detector array with 18.5 µ pixels, providing spectral content along one direction, and spatial content across the other. This eliminates the need for any form of spectral scanning mechanism or time sharing of spectral intervals. It enables smaller, lighter, instruments and a less complex, rugged, and stable opto-mechanical design, particularly well suited to the launch environment and long-term reliability on orbit.

A schematic of the general approach and design features specific to the SR module is shown on Fig. 2.

- compact Littrow configuration with large grating enables high spectral resolution

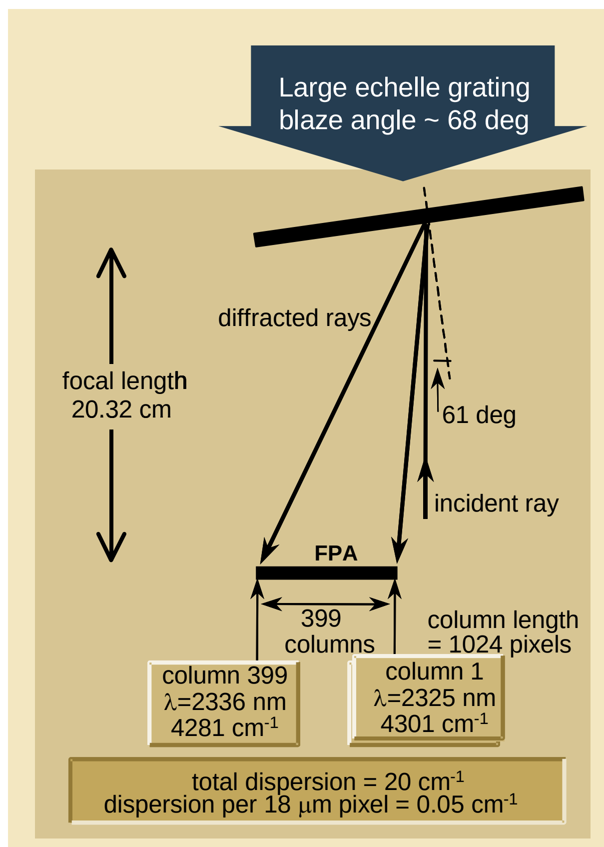

Fig. 2. Schematic illustrating the SR module design features

- wide field design optimizes coverage
- GMS exploits low noise, large format 2-D array technology
- GMS has no moving spectrometer mechanisms

IV. SCHEDULE AND STATUS

B. *Schedule*

We are now 16 months into the program. Due to long lead items and the funding profile, the modules build and test has been stretched into the second year. With completion scheduled for the third quarter.

The TIR module was scheduled first to completion since we had a suitable in house detector array for it, but not for the SR module. The detector array is the longest lead procurement item in these builds, therefore it was logical to first build the TIR module, and next the SR module. This approach was also consistent with the funding profile.

In the fourth quarter of the second year we are scheduled to conduct joint field tests with the University of Denver (DU). These will be conducted at the DU site. Simultaneously the TIMS and the highly calibrated DU FTIR will acquire sky looking data in the TIR region. Data will also be acquired simultaneously in the SR region from several sources including sunlight reflected from (1) a diffuser plate and also from (2) various terrain, e.g., looking across a valley at a mountain side.

These joint tests will provide validation for the TIMS spectral radiance measurements. These will be input to retrieval algorithms that we are developing with support of the IIP program. The retrievals will be compared with the DU retrievals for validation.

A second series of joint field tests will be conducted with DU in the second quarter of the third year. This will give us time for data analysis that will drive fine tuning of the

- calibration and retrieval algorithms
- instruments.

B. *Potential to take the next step, airborne TIMS*

Following the joint tests with DU the TIMS instrumentation would be ready for the next logical and very important development step, interface on to an aircraft for further testing. This would be conducted in a nadir viewing configuration that almost identically simulates the space view conditions. This would be allow to tune the algorithms for a wide range of conditions of solar illumination, variation in terrain albedos and elevations, various cloud fractions and aerosol, etc. This would also provide an opportunity to demonstrate the science value of the TIMS measurements such that the airborne TIMS would be ready for deployment in subsequent NASA Suborbital Science missions.

Funding for the airborne tests as described here is not part of the IIP program, but we have submitted a proposal to the ROSES AITT NRA that is designed to provide exactly this kind of support.

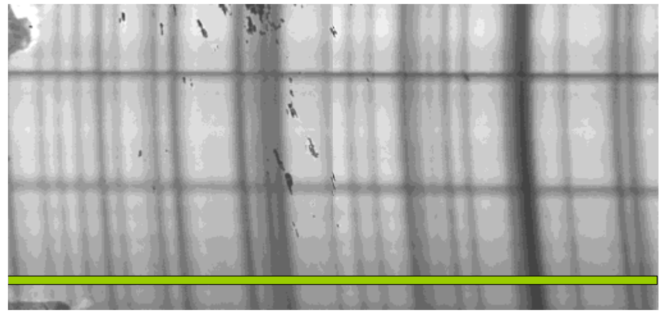

Fig. 3. Video display of zenith sky spectra

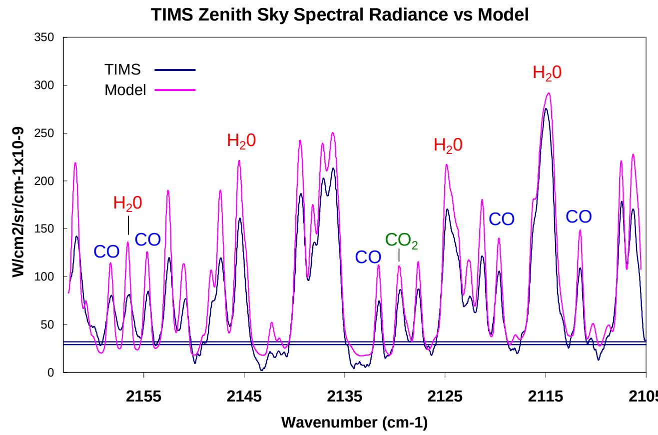

Fig. 4. 4.6 µ zenith sky spectra

C. *Status*

The TIR Module: The module is fully operational and has been used to acquire initial CO gas cell absorption spectra and zenith sky spectral radiances. We are in the process of fine-tuning focus, and positioning stray light baffles to maximize spectral resolution and sensitivity. A "first light" image, taken viewing the zenith sky is illustrated below in Fig. 3. It shows spectral features as they appear in video read–out, with spectral direction along horizontal rows and spatial distribution along vertical columns. Fig. 4 is a cross-sectional spectrum taken along the lower green bar, and is compared with a model identifying spectral features of CO, H_2O, and CO_2 in the observed zenith sky radiance.

Implicit in the comparison shown in Fig. 4 is our progress to date in calibration procedures and algorithms, and in modeling the spectral radiance. All these are necessary ingredients of the algorithms to process the data to level 1, calibrated radiance, and of the algorithms to process to level 2, species retrieval. These algorithms are necessary to support the joint tests and comparisons with DU. They are also necessary in developing an instrument concept for the space borne application, which will also be a product of our IIP study.

The SR Module: For this module all optical and mechanical design has been completed, and delivery has been taken for all major procurements. The build is underway and we expect to begin system level testing by July 2007, and be ready for deployment for the first joint field tests with DU in August.

Fig. 5. shows the SR module dewar along with optical elements and focal plane array hardware. Unlike the case for the TIR, the spectrometer can be constructed external to the dewar. This will considerably facilitate the alignment process.

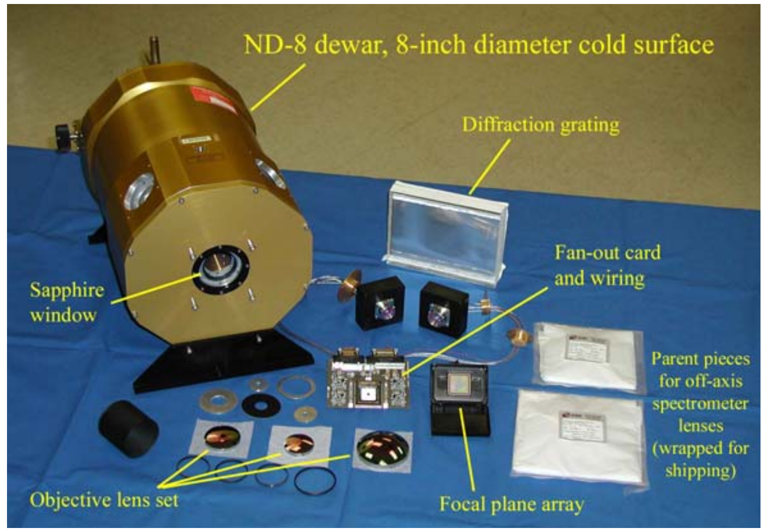

Fig. 5. SR module dewar and components

V CONCLUSIONS

As discussed in sections I and II the TIMS has the promise of providing very important space borne measurements that respond to the priorities established by [1]. For example, the TIMS would be an ideal candidate for deployment on the GEO-CAPE and/or GACM Missions as described by [1].

We are on track, and very much look forward to participate in the joint field tests with DU. These will provide the first step in verifying the utility and importance of the TIMS measurements.

ACKNOWDGMENT

This work is supported by the NASA ESTO Instrument Incubator Program.

REFERENCES

[1] Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, National Research Council; ISBN: 0-309-66900-6, 400 pages, 8 1/2 x 11, (2007).

[2] Kumer et al., Tropospheric infrared mapping spectrometers (TIMS) for Air Quality measurements Community Workshop on Air Quality Remote Sensing from Space: Defining an Optimum Observing Strategy, hosted by NCAR and held in Boulder, CO, 21-23 February, 2006, to generate a report for input to the NRC Decadal Survey, the website for the Kumer et al paper is: http://www.acd.ucar.edu/Meetings/Air_Quality_Remote_Sensing/Presentations/Posters/4.P.Kumer.pdf